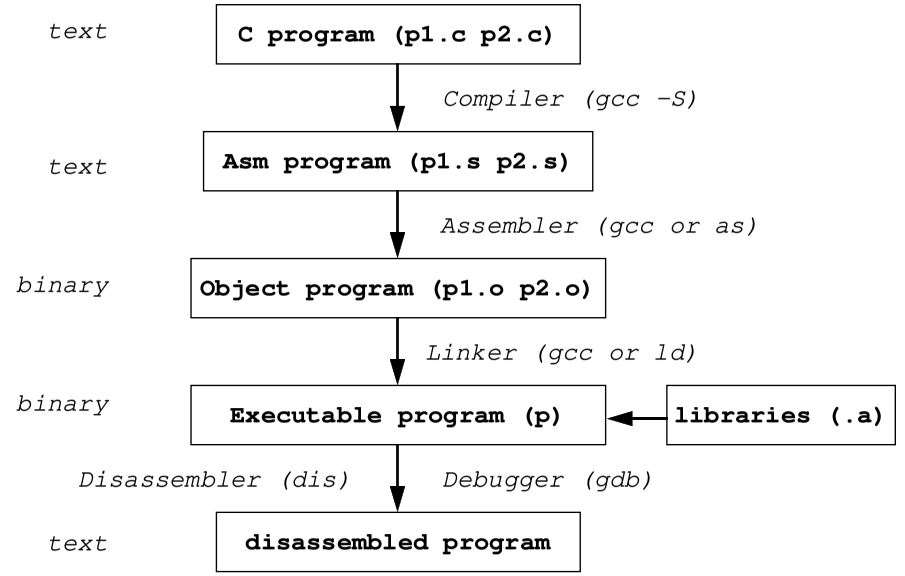
MIPS Programming
CS 740

Sept. 19, 1996

Topics

- Basics
- Control Flow
- Procedures
- Data Representations
- Instruction Formats

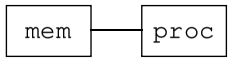
Translation Process



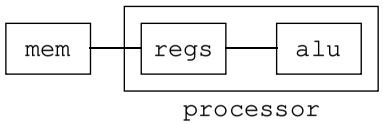
Abstract machines

Machine Model

C



ASM



Data

```
1) char
2) int, float
3) double
4) struct, array
5) pointer
```

```
1) byte
2) word
3) doubleword
4) contiguous word allocation
5) address of initial byte
```

Control

```
1) loops
2) conditionals
3) goto
```

```
3) branch
```


MIPS Register Convention

General Purpose Registers

- 32 total
- Store integers and pointers
- Fast access: 2 reads, 1 write in single cycle

Usage Conventions

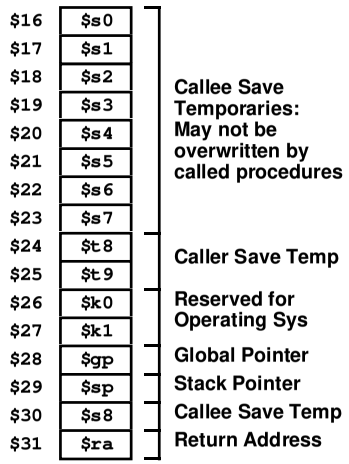
- Established as part of architecture
- Used by all compilers, programs, and libraries
- Assures object code compatibility
  - E.g., can mix Fortran and C

$0	$0	Constant 0
$1	$at	Reserved Temp.
$2	$v0	Return Values
$3	$v1	
$4	$a0	Procedure arguments
$5	$a1	
$6	$a2	
$7	$a3	
$8	$t0	Caller Save Temporaries: May be overwritten by called procedures
$9	$t1	
$10	$t2	
$11	$t3	
$12	$t4	
$13	$t5	
$14	$t6	
$15	$t7	

Registers (cont.)

Important Ones for Now

- $0 Constant 0
- $2 Return Value
- $3 Can use as temporary
- $4 First argument
- $5 Second argument
- $31 Return address



Program Representations

C Code

```
int gval;

void test1(int x, int y)
{
  gval = (x+x+x) - (y+y+y);
}
```

Obtain with command

```
gcc -O -S code.c
```

Produces file `code.s`

Compiled to Assembly

```
        .comm   gval,8

        .loc    1 7
        .ent    test1
test1:
        .frame  $sp,0,$31
        .mask   0x00000000,0
        .fmask  0x00000000,0
        addu    $3,$4,$4
        addu    $3,$3,$4
        addu    $2,$5,$5
        addu    $2,$2,$5
        subu    $3,$3,$2
        sw      $3,gval
        j       $31
        .end    test1
```


Prog. Representation (Cont.)

Object

```
0x400230 <test1>:
    0x00841821
    0x00a51021
    0x00451021
    0x00641821
    0x00621823
    0x03e00008
    0xaf838108
```

Disassembled

```
0x400230 <test1>:       addu $v1,$a0,$a0
0x400234 <test1+4>:     addu $v0,$a1,$a1
0x400238 <test1+8>:     addu $v0,$v0,$a1
0x40023c <test1+12>:    addu $v1,$v1,$a0
0x400240 <test1+16>:    subu $v1,$v1,$v0
0x400244 <test1+20>:    jr $ra
0x400248 <test1+24>:    sw $v1,-32504($gp)
```

Run gdb on object code

```
x/7 0x400230
```

```
dissassemble test1
```


Delayed Branches

C Code

```
int test2(int x, int y)
{
  return (x+x+x) - (y+y+y);
}
```

Compiled to Assembly

```
        .loc    1 12
        .ent    test2
test2:
        .frame  $sp,0,$31
        .mask   0x00000000,0
        .fmask  0x00000000,0
        addu    $2,$4,$4
        addu    $2,$2,$4
        addu    $3,$5,$5
        addu    $3,$3,$5
        .set    noreorder
        .set    nomacro
        j       $31
        subu    $2,$2,$3
        .set    macro
        .set    reorder

        .end    test2
```

Annotated Delayed Branch Code

C Code

```
int test2(int x, int y)
{
  return (x+x+x) - (y+y+y);
}
```

Annotated Assembly

```
test2:
        # x in $4, y in $5
        # Return result in $2
        addu    $2,$4,$4    # $2 = x+x
        addu    $2,$2,$4    # $2 += x
        addu    $3,$5,$5    # $3 = y+y
        addu    $3,$3,$5    # $3 += y
        J       $31         # (Delayed) return
        subu    $2,$2,$3    # with value $2-$3
```

Notation Convention

- **Upper case denotes delayed branch**
- **Lower case denotes normal branch**

For Exposition Only

- **Actual machine supports only delayed branches**
- **Regular ones converted by assembler**

Pointer Examples

C Code

```
int iaddp(int *xp, int *yp)
{
  int x = *xp;
  int y = *yp;
  return x + y;
}
```

Annotated Assembly

```
iaddp:
        lw      $2,0($4)  # $2 = *xp
        lw      $3,0($5)  # $3 = *yp
        J       $31       # (delayed) return
        addu    $2,$2,$3  # with value $2+$3
```

```
void incr(int *sum, int v)
{
  int old = *sum;
  int new = old+val;
  *sum = new;
}
```

```
incr:
        lw      $2,0($4)  # $2 = *sum
        #nop
        addu    $2,$2,$5  # $2+= v
        J       $31       # (delayed) return
        sw      $2,0($4)  # with *sum = $2
```


Array Indexing

C Code

```
int aref(int a[], int i)
{
  return a[i];
}
```

Annotated Assembly

```
aref:
        sll     $5,$5,2  # $5 = 4*i
        addu    $5,$5,$4 # $5 = &a[i]
        lw      $2,0($5) # return val. = a[i]
        j       $31      # Return
```

```
int garray[10];

int gref(int i)
{
  return garray[i];
}
```

```
        .comm   garray,40

gref:
    sll $4,$4,2       # $4 = 4*i
    lw  $2,garray($4) #Return val = garray[i]
    j   $31           # Return
```

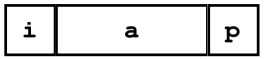
Disassembled:

```
0x40034c <gref>:        sll $a0,$a0,0x2
0x400350 <gref+4>:      lui $v0,4096
0x400354 <gref+8>:      addu $v0,$v0,$a0
0x400358 <gref+12>:     lw $v0,4304($v0)
0x40035c <gref+16>:     JR $ra
0x400360 <gref+20>:     nop
```


Structures & Pointers

C Code

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```




```
void addr(struct rec *r)
{
  int *loc;
  r->i = 1;
  loc = &r->a[r->i];
  r->p = loc;
  *(r->p) = 2;
  r->a[0] = 4;
  *(r->p+1) = 8;
}
```

Annotated Assembly

```
addr:
        li      $2,0x00000001 # $2 = 1
        sw      $2,0($4)      # r->i = 1
        addu    $2,$4,8       # $2 = &r->a[1]
        sw      $2,16($4)     # r->p = $2
        li      $2,0x00000002 # $2 = 1
        sw      $2,8($4)      # r->a[1] = 2
        lw      $2,16($4)     # $2 = r->p
        li      $3,0x00000004 # $3 = 4
        li      $5,0x00000008 # $4 = 8
        sw      $3,4($4)      # r->a[0] = 4
        J       $31           # Return
        sw      $5,4($2)      # setting
                              # *(r->p+1) = 8
```

MIPS Implemented Branches

Formats

- **b*COND* Rs, Rt, *label***
  - *Cond* : Branch condition
- **b*COND* Rs, *label***
  - *Cond* : Branch condition, relative to zero

Conditions

		Reg. Arguments
beq	**EQual**	**2**
bne	**Not Equal**	**2**
bgez	**Greater or Equal to Zero**	**1**
bgtz	**Greater Than Zero**	**1**
blez	**Less or Equal to Zero**	**1**
bltz	**Less Than Zero**	**1**

Implementation

- **All have single cycle delay slot**

Branch Notation Convention

Caveat

- **For exposition only**
- **Not machine-readable assembly code**

Conventional Branches

- **Lower Case**
  - `j`, `jr`, `beq`, `bltz`, etc.
- **If branch taken, following instruction *not* executed**
- **Allowed in assembly**

Delayed Branches

- **Upper Case**
  - `J`, `JR`, `BEQ`, `BLTZ`, etc.
- **Following instruction executed whether or not branch taken**
- **Actually implemented**
- **Use assembler directives to enable/disable.**

Conditional Example

C Code

```
int max(int x, int y)
{
  return (x < y) ? y : x;
}
```

Compiled

```
max:
    # x in $4, y in $5
    slt     $2,$4,$5    # $4 < $5 ?
    beq     $2,$0,$L2   # if not, goto $L2
    move    $4,$5       # else $4 = y
$L2:
    J       $31         # Return
    move    $2,$4       # with $4
```

Disassembled

```
0x400230 <max>:         slt $v0,$a0,$a1
0x400234 <max+4>:       BEQ $v0,$zero,0x400240 <max+16>
0x400238 <max+8>:       nop
0x40023c <max+12>:      move $a0,$a1
0x400240 <max+16>:      JR $ra
0x400244 <max+20>:      move $v0,$a0
```


Loop Example

C Code

```
int fact(int x)
{
  int result = 1;
  while (x >= 2)
    result *= x--;
  return result;
}
```

Handwritten Assembly

```
fact:
        li      $2,0x1
        blt     $4,2,$L5 # Skip if x < 2
$L4:
        mul     $2,$4    # result *= x
        addi    $4,$4,-1 # x--
        bge     $4,2,$L4 # loop if x >= 2
$L5:
        j       $31      # return
        .end    fact
```

Macro-Expanded Operations

blt $Rs, $Rt, label

Branch if **$Rs < $Rt**

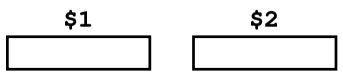
mul $Rdest, $Rsrc

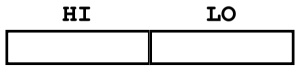
$Rdest *= $Rsrc

MIPS Integer Multiplication

Multiplication Operation

- **Arguments: 32-bits each**
  - Unsigned: `multu $1, $2`
  - Signed: `mult $1, $2`
- **Product: 64 bits**
  - Stored in special register pair
  - High & Low order words
- **Retrieve result with special instructions**
  - `mfhi $3`
  - `mflo $2`
- **SLOW!**
  - Many clock cycles





Assembled Loop Code

Handwritten Assembly

```
        li      $2,0x1
        blt     $4,2,$L5 # Skip if x < 2
$L4:
        mul     $2,$4    # result *= x
        addi    $4,$4,-1 # x--
        bge     $4,2,$L4 # loop if x >= 2
$L5:
        j       $31      # return
```

Macro expansion uses register `$1` (`$at`) as temporary

Disassembled

```
0x400ba0 <hfact>:       slti $at,$a0,2
0x400ba4 <hfact+4>:     BNE $at,$zero,0x400bc4 <hfact+36>
0x400ba8 <hfact+8>:     li $v0,1
0x400bac <hfact+12>:    multu $v0,$a0
0x400bb0 <hfact+16>:    addi $a0,$a0,-1
0x400bb4 <hfact+20>:    slti $at,$a0,2
0x400bb8 <hfact+24>:    mflo $v0
0x400bbc <hfact+28>:    BEQ $at,$zero,0x400bac <hfact+12>
0x400bc0 <hfact+32>:    nop
0x400bc4 <hfact+36>:    JR $ra
0x400bc8 <hfact+40>:    nop
```


Translation of `for` Loop

C Code

```
/* Find max ele. in array */
int amax(int a[], int count)
{
  int i;
  int result = a[0];
  for (i = 1; i < count; i++)
    if (a[i] > result)
      result = a[i];
  return result;
}
```

`for (`*init*`; `*test*`; `*update*`)`

body

`init;`

`while(`*test*`)`

`{ `*body*` ; `*update*` }`

Annotated Assembly

```
    # *a in $4, count in $5
    # Use $6 for i, $7 for result
    lw      $7,0($4)        # result = a[0]
    li      $6,0x00000001   # i = 1
    slt     $2,$6,$5        # if !(i < count)
    beq     $2,$0,$L6       # then goto $L6
$L9:
    sll     $2,$6,2
    addu    $2,$2,$4        # $R2 = &a[i]
    lw      $3,0($2)        # $R3 = a[i]
    slt     $2,$7,$3     # if !(result < $R3)
    BEQ     $2,$0,$L7       # then goto $L7
    addu    $6,$6,1         # with count++
    move    $7,$3          # else result = $R3
$L7:
    slt     $2,$6,$5        # if i < count
    bne     $2,$0,$L9       # then goto $L9
$L6:
    J       $31             # return
    move    $2,$7           # with result
```


Compiling Switch Statements

C Code

```
typedef enum
  {ADD, MULT, MINUS, DIV, MOD, BAD}
op_type;

char unparse_symbol(op_type op)
{
  switch (op) {
  case ADD :
    return '+';
  case MULT:
    return '*';
  case MINUS:
    return '-';
  case DIV:
    return '/';
  case MOD:
    return '%';
  case BAD:
    return '?';
  }
}
```

Implementation Options

- **Series of conditionals**
  - Good if few cases
  - Slow if many
- **Jump Table**
  - Lookup branch target
  - Avoids conditionals
  - Possible when cases are small integer constants
- **GCC**
  - Picks one based on case structure

Switch Statement Example

C Code

```
typedef enum
  {ADD, MULT, MINUS, DIV, MOD, BAD}
op_type;

char unparse_symbol(op_type op)
{
  switch (op) {
  case ADD :
    return '+';
  case MULT:
    return '*';
  case MINUS:
    return '-';
  case DIV:
    return '/';
  case MOD:
    return '%';
  case BAD:
    return '?';
  }
}
```

Enumerated Values

```
ADD     0
MULT    1
MINUS   2
DIV     3
MOD     4
BAD     5
```

Assembly: Setup

```
# op in $R4
li    $2,0x00000004
sltu  $2,$2,$4       #if (4 < op)
BNE   $2,$0,$L144    #then goto $L144
li    $2,0x0000003f # with '?'
sll   $2,$4,2
lw    $2,$L143($2)   # $2 = &tab[op]
j     $2             # goto $2
```


Jump Table

Table Contents

```
$L143:
        .word   $L137
        .word   $L138
        .word   $L139
        .word   $L140
        .word   $L141
```

Enumerated Values

```
ADD     0
MULT    1
MINUS   2
DIV     3
MOD     4
BAD     5
```

Targets

```
$L137:
   J    $L144          # goto $L144
   li   $2,0x0000002b  # with '+'
$L138:
   J    $L144          # goto $L144
   li   $2,0x0000002a  # with '*'
$L139:
   J    $L144          # goto $L144
   li   $2,0x0000002d  # with '-'
$L140:
   J    $L144          # goto $L144
   li   $2,0x0000002f  # with '/'
$L141:
   li   $2,0x00000025  # $2 = '%'
```

Completion

```
$L144:
        j       $31   # return
```


Stack-Based Languages

Languages that support recursion

- E.g.: C, Pascal

Stack Allocated in *Frames*

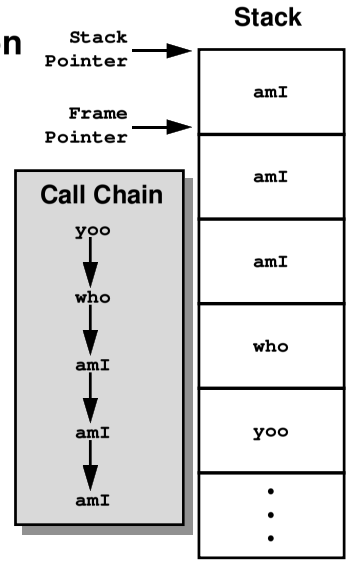
- State for procedure invocation
  - Return point, arguments, locals

Code Example

```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

```
who(…)
{
    •
    •
    amI();
    •
    •
}
```

```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```



Saving Conventions

When procedure `yoo` calls `who`

- `yoo` is the *caller*
- `who` is the *callee*

Caller Save

- If `yoo` wants value in register before & after `who` returns
  - Save it on the stack before calling who
  - Restore after who returns

Callee Save

- If `who` wants to use register
  - Save current register value on stack on entry
  - Restore when returning

Saving Examples

Caller Save

- **Caller must save/restore**
- **Callee can clobber**

```
yoo:
     li $8, 17
       • • •
     sw $8, 20($sp)
     jal who
     lw $8, 20($sp)
       • • •
     mov $2, $8
     j $31
```

```
who:
     li $8, 57
       • • •
     j $31
```

Callee Save

- **Callee must save/restore**

```
yoo:
     li $16, 17
       • • •
     jal who
       • • •
     mov $2, $16
     j $31
```

```
who:
     sw $16, 20($sp)
     li $16, 57
       • • •
     lw $16, 20($sp)
     j $31
```

What's wrong with above code?

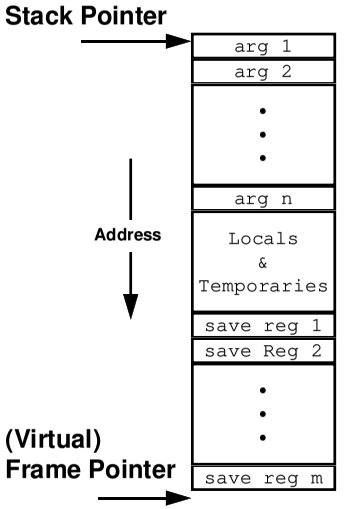
MIPS Stack Frame

Conventions

- **Agreed by all program/compiler writers**
  - Allows linking between different compilers
  - Allows symbolic debugging tools

Run Time Stack

- **Save context**
  - Registers
- **Storage for local variables**
- **Parameters to called functions**
- **Required to support recursion**



Stack Frame Requirements

Procedure Categories

- **Leaf procedures that do not use stack**
  - Do not call other procedures
  - Can fit all temporaries in caller-save registers
- **Leaf procedures that use stack**
  - Do not call other procedures
  - Need stack for temporaries
- **Non-leaf procedures**
  - Must use stack (to save $31 at the least)

Stack Frame Structure

- **Must be multiple of 8 bytes**
- **Must have space for saving argument registers $4, …, $7**
  - Even if don't store anything there
  - Used by symbolic debuggers

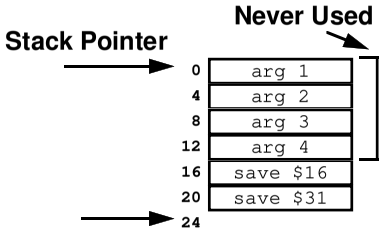
Optimized Stack Frame Example

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```

Compiled -O: Frame Setup

```
rfact:
        .frame  $sp,24,$31
        .mask   0x80010000,-4
        .fmask  0x00000000,0
        subu    $sp,$sp,24
        sw      $31,20($sp)
        sw      $16,16($sp)
```

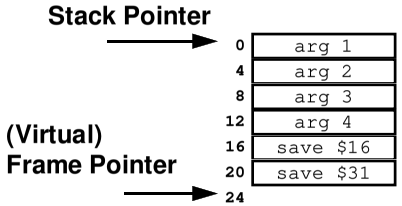


- **Stack frame 24 bytes**
- **Virtual frame ptr at sp + 24**
- **Save registers $31 and $16**
- **Starting at sp + 24 - 4**
- **No floating pt. regs. used**

Opt. Stack Frame Example (Cont.)

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```



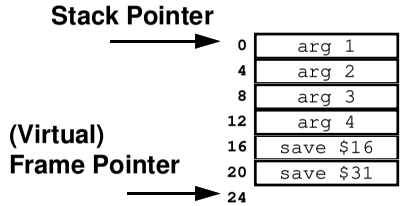
Compiled -O: Body

```
    move  $16,$4         # Save x
    slt   $2,$16,2       # if x < 2
    BNE   $2,$0,$L3      # then goto $L3
    li    $2,0x00000001  # with return val 1
    JAL   rfact          # Call rfact
    subu  $4,$16,1       # on x-1
    mult  $16,$2         # x * return val
    mflo  $2             # as return val
```


Opt. Stack Frame Example (Cont.)

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```



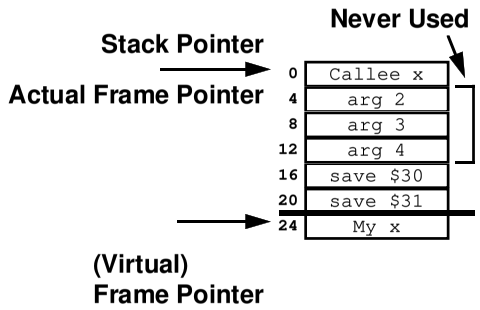
Compiled -O: Completion

```
$L3:
    lw    $31,20($sp)
    lw    $16,16($sp)
    addu  $sp,$sp,24
    j     $31
```


Unopt. Stack Frame Example:

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```



Compiled: Frame Setup

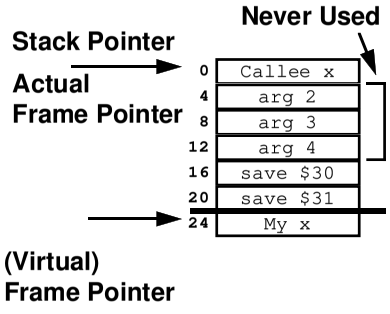
```
rfact:
    .frame  $fp,24,$31
    .mask   0xc0000000,-4
    .fmask  0x00000000,0
    subu    $sp,$sp,24
    sw      $31,20($sp)
    sw      $fp,16($sp)
    move    $fp,$sp
    sw      $4,24($fp)
```

- Stack frame 24 bytes
- Actual frame pointer $fp uses $30
- Virtual frame ptr at $fp + 24
- Save registers $31 and $30
- Starting at $fp + 24 - 4
- No floating pt. regs. used

Unopt. Stack Frame Example (Cont.)

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```



Compiled: Body

```
    lw      $2,24($fp)     # Get argument x
    slt     $3,$2,2        # If !(x < 2)
    beq     $3,$0,$L2      # then goto $L2
    li      $2,0x00000001  # return val 1
    j       $L1            # goto $L1
$L2:
    lw      $3,24($fp)     # Get argument x
    subu    $2,$3,1        # Subtract 1
    move    $4,$2          # assign to arg1
    jal     rfact          # Call rfact
    lw      $3,24($fp)     # Get argument x
    mult    $2,$3          # x * return val
    mflo    $2             # is return val
    j       $L1
```

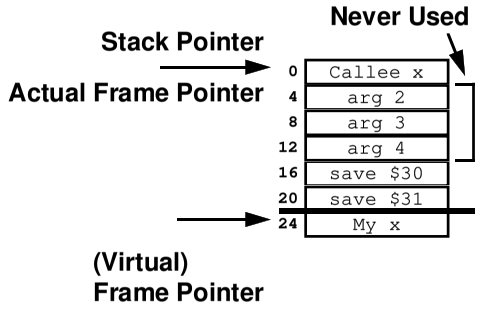
Unopt. Stack Frame Example (Cont.)

C Code

```
/* Recursive factorial */
int rfact(int x)
{
  if (x <= 1)
    return 1;
  return x * rfact(x-1);
}
```

Compiled: Completion

```
  move    $sp,$fp
  lw      $31,20($sp)
  lw      $fp,16($sp)
  addu    $sp,$sp,24
  j       $31
```



Local Storage Example

C Code

```
char *stuff_it
  (char c0, char c1, char c2,
   char c3, char c4, char c5,
   char c6)
{
  char buf[7]; /* Not enough! */
  int i = 0;
  char *result;
  buf[i++] = c0;
  buf[i++] = c1;
  buf[i++] = c2;
  buf[i++] = c3;
  buf[i++] = c4;
  buf[i++] = c5;
  buf[i++] = c6;
  buf[i++] = 0;
  result = (char *) malloc(i);
  strcpy(result, buf);
  return result;
}
```

```
char *do_it()
{
  return stuff_it
    ('1','5','-','7','4','0','!');
}
```

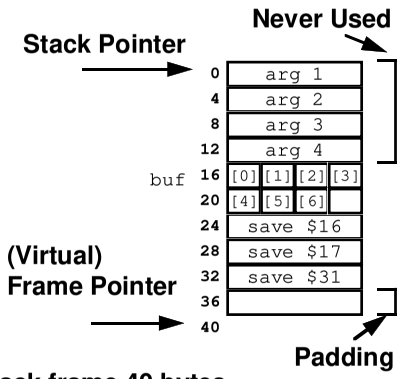

Local Storage Example

C Code: Initial

```
char *stuff_it
  (char c0, char c1, char c2,
   char c3, char c4, char c5,
   char c6)
{
  char buf[7]; /* Not enough! */
  int i = 0;
  char *result;
```

Compiled -O: Frame Setup

```
stuff_it:
  .frame  $sp,40,$31
  .mask   0x80030000,-8
  .fmask  0x00000000,0
  .subu   $sp,$sp,40
  sw      $31,32($sp)
  sw      $17,28($sp)
  sw      $16,24($sp)
```



- Stack frame 40 bytes
- Virtual frame ptr at $sp + 40
- Save registers $31, $17, $16
  - Starting at $sp + 40 - 8
- No floating pt. regs. used

Local Storage Example (Cont.)

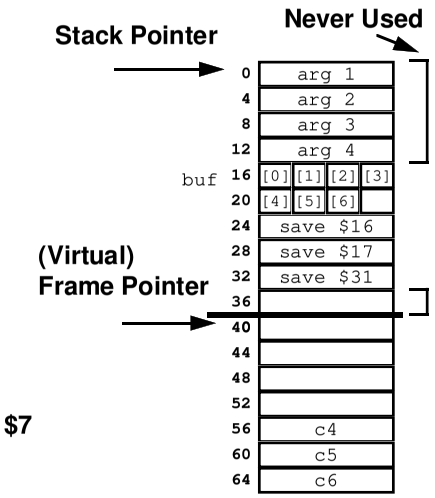
C Code: Argument Retrieval

```
char *stuff_it
  (char c0, char c1, char c2,
   char c3, char c4, char c5,
   char c6)
```

Compiled -O: Args 5–7

```
  lbu     $2,56($sp)
  lbu     $3,60($sp)
  lbu     $8,64($sp)
```

- c0 … c3 passed in registers $4 … $7



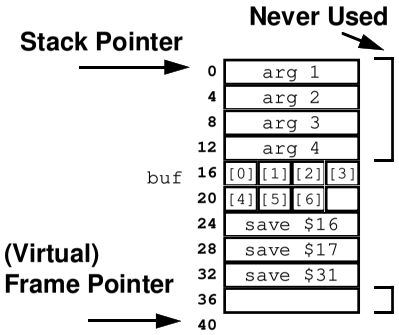
Local Storage Example (Cont.)

C Code: Local Setup

```
buf[i++] = c0;
buf[i++] = c1;
buf[i++] = c2;
buf[i++] = c3;
buf[i++] = c4;
buf[i++] = c5;
buf[i++] = c6;
buf[i++] = 0;
```

Compiled -O

```
addu    $17,$sp,16   # $17 = &buf
sb      $4,16($sp)   # buf[0] = c0
sb      $5,17($sp)   # buf[1] = c1
sb      $6,18($sp)   # buf[2] = c2
sb      $7,19($sp)   # buf[3] = c3
sb      $0,23($sp)   # buf[7] = 0   !!
sb      $2,20($sp)   # buf[4] = c4
sb      $3,21($sp)   # buf[5] = c5
sb      $8,22($sp)   # buf[6] = c6
```



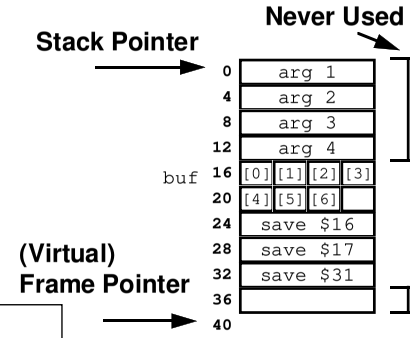
Local Storage Example (Cont.)

C Code: Calls

```
result = (char *) malloc(i);
strcpy(result, buf);
```

Compiled -O

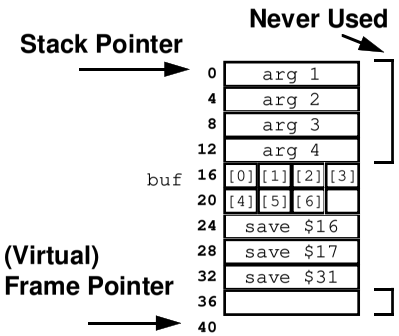
```
li      $4,0x00000008  # i = 8
jal     malloc         # malloc(i)
move    $16,$2         # $16 = result
move    $4,$16
JAL     strcpy         # strcpy(result,
move    $5,$17         #   , buf)
move    $2,$16         # return val result
```



Local Storage Example (Cont.)

Completion

```
lw      $31,32($sp)
lw      $17,28($sp)
lw      $16,24($sp)
addu    $sp,$sp,40
j       $31
```



Basic Data Types

Integral

- Stored & operated on in general registers
- Signed vs. unsigned depends on instructions used

MIPS	Bytes	C
byte	1	`[unsigned] char`
half word	2	`[unsigned] short`
word	4	`[unsigned] [long] int`
		pointer

Floating Point

- Stored & operated on in floating point registers
- Special instructions for two different precisions

MIPS	Bytes	C
single precision	4	`float`
double precision	8	`double`

Floating Point Unit

Implemented as Coprocessor 1

- Hardware to add, multiply, and divide
- Floating point data registers
- Various control & status registers

Floating Point Values

- Single precision (C `float`): 32 bits
- Double precision (C `double`): 64 bits

Floating Point Data Registers

- 32 registers, each 4 bytes
- Allocated in pairs
  - Even for single precision

$f0	$f1	Return Values
$f2	$f3	
$f4	$f5	Caller Save Temporaries: May be overwritten by called procedures
$f6	$f7	
$f8	$f9	
$f10	$f11	
$f12	$f13	Procedure arguments
$f14	$f15	
$f16	$f17	Caller Save Temporaries:
$f18	$f19	
$f20	$f21	Callee Save Temporaries: May not be overwritten by called procedures
$f22	$f23	
$f24	$f25	
$f26	$f27	
$f28	$f29	
$f30	$f31	

Floating Point Code Example

Compute Inner Product of Two Vectors

- Single precision

```
float inner_prodF
  (float x[], float y[], int n)
{
  int i;
  float result = 0.0;
  for (i = 0; i < n; i++) {
    result += x[i] * y[i];
  }
  return result;
}
```

```
inner_prodF:
  subu    $sp,$sp,8 # Allocate stack frame
  mtc1    $0,$f4    # result = 0.0
  BLEZ    $6,$L3    # if n <= 0 goto $L3
  move    $3,$0     # i = 0
$L5:
  l.s     $f0,0($4) # $f0 = x[i]
  l.s     $f2,0($5) # $f2 = y[i]
  mul.s   $f0,$f0,$f2  # $f0 = x[i] * y[i]
  addu    $5,$5,4   # y+i++
  add.s   $f4,$f4,$f0  # result += $f0
  addu    $3,$3,1   # i++
  slt     $2,$3,$6  # if i < n
  BNE     $2,$0,$L5 # then loop
  addu    $4,$4,4   # with x+i++
$L3:
  mov.s   $f0,$f4   # return val = result
  addu    $sp,$sp,8 # Deallocate frame
  j       $31       # return
```


Double Precision

```
double inner_prodD
  (double x[], double y[],
   int n)
{
  int i;
  double result = 0.0;
  for (i = 0; i < n; i++) {
    result += x[i] * y[i];
  }
  return result;
}
```

```
inner_prodD:
  # result in $f4,5
  mtc1    $0,$f4    # result = 0.0
  mtc1    $0,$f5
  subu    $sp,$sp,8 # allocate stack frame
  BLEZ    $6,$L8    # if n <= 0 goto $L8
  move    $3,$0     # i = 0
$L10:
  l.d     $f2,0($4) # $f2,3 = x[i]
  l.d     $f0,0($5) # $f0,1 = y[i]
  mul.d   $f2,$f2,$f0 # $f2,3 *= y[i]
  addu    $5,$5,8   # y+i++
  add.d   $f4,$f4,$f2 # result *= $f2,f3
  addu    $3,$3,1     # i++
  slt     $2,$3,$6    # if i < n
  BNE     $2,$0,$L10  # then loop
  addu    $4,$4,8     # with x+i++
$L8:
  mov.d   $f0,$f4     # return val = result
  addu    $sp,$sp,8   # deallocate frame
  j       $31         # return
```


Disassembled

```
0x400250 <inner_prodD>:         mtc1 $zero,$f4
0x400254 <inner_prodD+4>:       mtc1 $zero,$f5
0x400258 <inner_prodD+8>:       addiu $sp,$sp,-8
0x40025c <inner_prodD+12>:      BLEZ $a2,0x400290 <inner_prodD+64>
0x400260 <inner_prodD+16>:      move $v1,$zero
0x400264 <inner_prodD+20>:      lwc1 $f2,0($a0)
0x400268 <inner_prodD+24>:      lwc1 $f3,4($a0)
0x40026c <inner_prodD+28>:      lwc1 $f0,0($a1)
0x400270 <inner_prodD+32>:      lwc1 $f1,4($a1)
0x400274 <inner_prodD+36>:      addiu $v1,$v1,1
0x400278 <inner_prodD+40>:      mul.d $f2,$f2,$f0
0x40027c <inner_prodD+44>:      slt $v0,$v1,$a2
0x400280 <inner_prodD+48>:      addiu $a1,$a1,8
0x400284 <inner_prodD+52>:      add.d $f4,$f4,$f2
0x400288 <inner_prodD+56>:      BNE $v0,$zero,0x400264 <inner_prodD+20>
0x40028c <inner_prodD+60>:      addiu $a0,$a0,8
0x400290 <inner_prodD+64>:      mov.d $f0,$f4
0x400294 <inner_prodD+68>:      JR $ra
0x400298 <inner_prodD+72>:      addiu $sp,$sp,8
```

Structure Allocation

Principles

- **Allocate space for structure elements contiguously**
- **Access fields by offsets from initial location**
  - Offsets determined by compiler

```
typedef struct {
  char c;
  int i[2];
  double d;
} struct_ele, *struct_ptr;
```

Alignment

Requirements

- **Data type requires K bytes**
- **Address must be multiple of K**

Specific Cases

- **Word data address must be multiple of 4**
- **Doubleword data address must be multiple of 8**

Reason

- **Memory accessed by (aligned) words**
  - Inefficient to load or store data that spans word boundaries
  - Virtual memory very tricky when datum spans 2 pages

Compiler

- **Inserts gaps within structure to ensure correct alignment of fields**

Structure Access

C Code

```
char struct_c(struct_ptr p)
{
  return p->c;
}
```

```
int *struct_i(struct_ptr p)
{
  return p->i;
}
```

```
int struct_i1(struct_ptr p)
{
  return p->i[1];
}
```

```
double struct_d(struct_ptr p)
{
  return p->d;
}
```

Assembler

```
  lb    $2,0($4)   # 1st byte
  j     $31
```

```
  J     $31
  addu  $2,$4,4    # addr of 4th byte
```

```
  lw    $2,8($4)   # word at 8th byte
  j     $31
```

```
  l.d   $f0,16($4) # dblewd at 16th by.
  j     $31
```


Arrays vs. Pointers

Recall

- **Can access stored data either with pointer or array notation**
- **Differ in how storage allocated**
  - Array declaration allocates space for array elements
  - Pointer declaration allocates space for pointer only

```
typedef struct {
  char c;
  int *i;
  double d;
} pstruct_ele,
  *pstruct_ptr;
```

C Code for Allocation

```
pstruct_ptr pstruct_alloc(void)
{
  pstruct_ptr result = (pstruct_ptr)
           malloc(sizeof(pstruct_ele));
  result->i = (int *)
           calloc(2, sizeof(int));
  return result;
}
```

Accessing Through Pointer

C Code

```
int *pstruct_i(pstruct_ptr p)
{
  return p->i;
}
```

Assembler

```
  lw     $2,4($4)   # word at 4th byte
  j      $31
```

```
int pstruct_i1(pstruct_ptr p)
{
  return p->i[1];
}
```

```
  # i = word at 4th byte from p
  lw     $2,4($4)
  # Retrieve word at 4th byte from i
  lw     $2,4($2)
  j      $31
```


Arrays

Principles

- **Allocated by repeating allocation for array type**
- **Accessed by computing address of element**
  - Attempt to optimize
    - » Minimize use of multiplication
    - » Exploit values determined at compile time

C Code

```
/* Index into array of
   struct_ele's */
struct_ptr a_index
    (struct_ele a[], int idx)
{
  return &a[idx];
}
```

Assembler

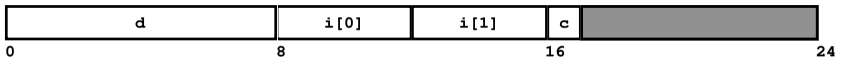
```
  sll    $2,$5,1
  addu   $2,$2,$5
  sll    $2,$2,3     # $2 = 24 * idx
  J      $31         # return
    # with a + (scaled) idx
  addu   $2,$4,$2
```


Aligning Array Elements

Requirement

- **Must make sure alignment requirements met when allocate array of structures**
- **May require inserting unused space at end of structure**

```
typedef struct {
  double d;
  int i[2];
  char c;
} rev_ele, *rev_ptr;
```



Nested Allocations

Principles

- **Can nest declarations of arrays and structures**
- **Compiler keeps track of allocation and access requirements**

```
typedef struct {
  int x;
  int y;
} point_ele, *point_ptr;

typedef struct {
  point_ele ll;
  point_ele ur;
} rect_ele, *rect_ptr;
```

Nested Allocation (cont.)

C Code

```
int area(rect_ptr r)
{
  int width = r->ur.x - r->ll.x;
  int height = r->ur.y - r->ll.y;
  return width * height;
}
```

Assembler

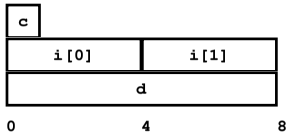
```
  lw     $2,8($4)    # $2 = ur.x
  lw     $3,0($4)    # $3 = ll.x
  subu   $2,$2,$3    # $2 = width
  lw     $3,12($4)   # $3 = ur.y
  lw     $4,4($4)    # $4 = ll.y
  subu   $3,$3,$4    # $3 = height
  mult   $2,$3
  mflo   $2          # width * height
  j      $31
```


Union Allocation

Principles

- Overlay union elements
- Allocate according to largest element
- Programmer responsible for collision avoidance

```
typedef union {
  char c;
  int i[2];
  double d;
} union_ele, *union_ptr;
```



Byte Ordering

Idea

- Bytes in word numbered 0 to 3
- Which is most (least) significant?
- Can cause problems when exchanging binary data between machines

Big Endian

- Byte 0 is most, 3 is least
- IBM 360/370, Motorola 68K, Sparc

Little Endian

- Byte 0 is least, 3 is most
- Intel x86, VAX

MIPS

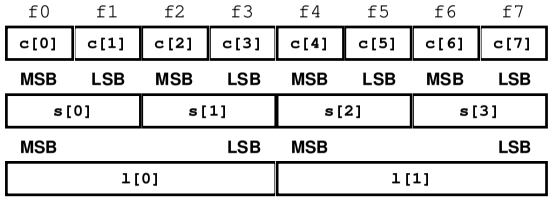
- Can be configured either way
- DECStation's are little endian

Byte Ordering Example

```
union {
  unsigned char c[8];
  unsigned short s[4];
  unsigned long l[2];
} dw;
int i;
for (i = 0; i < 8; i++)
  dw.c[i] = 0xf0 + i;
printf("Characters 0-7 == [0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x]\n",
       (long) dw.c[0], (long) dw.c[1], (long) dw.c[2], (long) dw.c[3],
       (long) dw.c[4], (long) dw.c[5], (long) dw.c[6], (long) dw.c[7]);
printf("Shorts 0-3 == [0x%x,0x%x,0x%x,0x%x]\n",
       (long) dw.s[0], (long) dw.s[1], (long) dw.s[2], (long) dw.s[3]);
printf("Longs 0-1 == [0x%x,0x%x]\n",
       dw.l[0], dw.l[1]);
```

Byte Ordering Example (cont.)

Big Endian

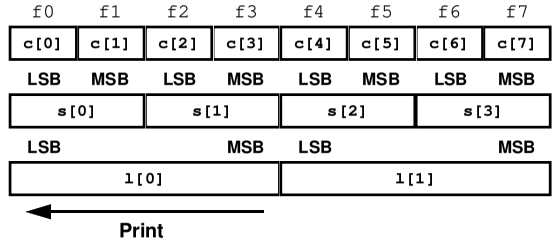


Output on Sun:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf0f1,   0xf2f3,   0xf4f5,   0xf6f7   ]
Longs      0-1 == [0xf0f1f2f3,         0xf4f5f6f7         ]
```


Byte Ordering Example (cont.)

Little Endian



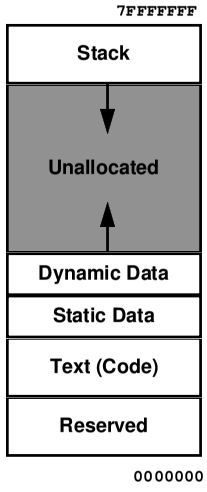
Output on DecStation:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,   0xf3f2,   0xf5f4,   0xf7f6   ]
Longs      0-1 == [0xf3f2f1f0,         0xf7f6f5f4         ]
```


MIPS Memory Layout

Segments

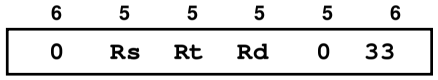
- **Stack**
  - Grows down from top
  - Implements runtime stack
- **Data**
  - Static space for global variables
    - » Allocation determined at compile time
  - Dynamic space for runtime allocation
    - » E.g., using malloc
- **Text**
  - Stores machine code for program
- **Reserved**
  - Used by operating system
    - » I/O devices, process info, etc.



Instruction Formats

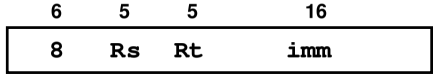
Arithmetic

- `addu Rd, Rs, Rt`
- **Similar for shift, Booleans, and comparisons**



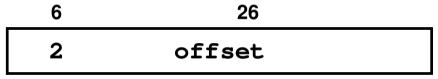
Constant-Manipulating

- `addi Rs, Rt, imm`
- **Only have 16-bit constant**

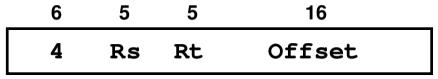


Jump

- `j offset`

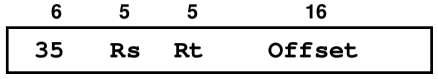


- `beq Rs, Rt, offset`
- **PC relative**



Load/Store

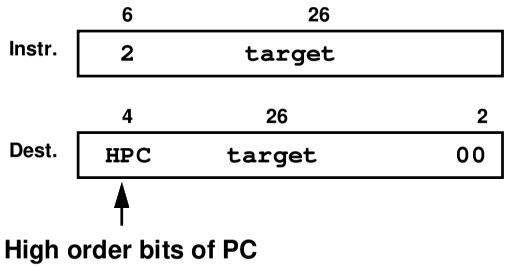
- `lw Rt, Offset(Rs)`



Specifying Jump Targets

Jump (and link)

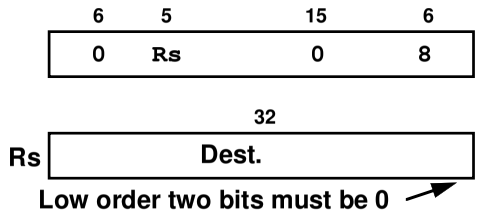
```
j target
```



Jump (and link) Register

```
jr Rs
```

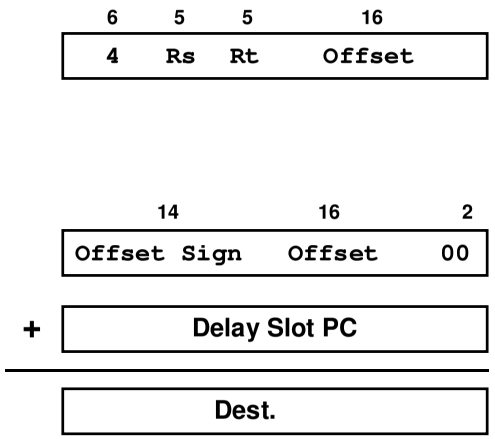
- Rs holds dest.



Specifying Branch Targets

Branch

```
beq Rs, Rt, offset
```



RISC Principles Summary

Simple & Regular Instructions

- **Small number of uniform formats**
- **Each operation does just one thing**
  - Memory access, computation, conditional, etc.

Encourage Register Usage over Memory

- **Operate on register data**
  - Load/store architecture
- **Procedure linkage**

Rely on Optimizing Compiler

- **Data allocation & referencing**
- **Register allocation**
- **Improve efficiency of user's code**
- **Dealing with implementation artifacts**
  - e.g., branch delay slots